Learning from a Wizard: Lessons from Nikola Tesla for Engineering Students

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One of the most flamboyant characters in the history of technology is the electrical inventor, Nikola Tesla (1856-1943). The inventor of the alternating current (AC) motor and an early pioneer in radio, Tesla was a highly talented rival of Edison who became a celebrity in the 1890s. During his heyday, the newspapers presented Tesla as a wizard who tamed electricity by means of mystical and intuitive powers. Tesla loved the publicity and deliberately cultivated his image as an eccentric genius.[1]

Over the years, Tesla has enjoyed a curious and mixed legacy. On the one hand, he is acknowledged by engineers as the father of the AC motor and in 1956, "Tesla" was adopted as the name for the unit of measure for the flux density of magnetic fields. Tesla's legacy is honored and promoted by the Tesla Memorial Society of New York and a group on Long Island is working to establish a science museum in Tesla's laboratory at Wardenclyffe.[2] On the other hand, thanks to the many colorful and exaggerated predictions he made about his inventions, Tesla has become a patron saint for New Age groups. Fascinated by Tesla's claims of using mystical powers to uncover the secrets of the universe, these fans contend that powerful individuals such as Edison and Morgan conspired to keep Tesla from perfecting his inventions. And there is even a rock band named Tesla.

But despite all the hype, Tesla was a highly skilled inventor and engineer, and his career offers valuable lessons for engineering students. An examination of how he developed his AC motor in the 1880s reveals much about what is involved in creating new technology. As you will see, these lessons come from not only looking at the historical details of Tesla's life but also how his early AC motors actually worked.

Visions of Motors

Tesla was born on July 10, 1856 to a Serbian family living in the military frontier district of the Austro-Hungarian Empire, in what is today Croatia. Tesla's father was a Serbian Orthodox priest who hoped his son would follow in his footsteps. As a teenager, Nikola was stirred by a faith in science and he instead pursued engineering at the Joanneum Polytechnic School in Graz, Austria.[3] There he eagerly attended the lectures in physics given by Professor Jacob Poeschl.

It was during Poeschl's lectures in 1876-7, that Tesla became interested in his first and most important invention, an AC motor. While watching his professor trying to control the sparking caused by a commutator on a direct current (DC) motor, Tesla suggested that it might be possible to design a motor without a commutator. Annoyed by Tesla's impudence, Poeschl lectured on the impossibility of creating such a motor, concluding "Mr. Tesla may accomplish great things, but he certainly never will do this."[4] Poeschl intended that his remarks should curb Tesla's flights of fancy but they instead stoked the fires of his ambition. As he pursued his studies in Graz and then Prague, Tesla puzzled about how to make a spark-free motor. In 1882, he moved to Budapest, Hungary in order to help install an Edison telephone exchange.

Rather than build actual motors, though, Tesla preferred to picture them in his mind and imagine them running. In 1882, while on a walk in Budapest's Városliget or City Park with his close friend, Anthony Szigeti, Tesla hit upon the perfect idea for his motor--a rotating magnetic field.[5] Up to this time, inventors had designed motors in which the magnetic field of the stator was kept constant and the magnetic field in the rotor was changed by means of a commutator. Tesla's insight was to reverse standard practice: rather than changing the magnetic poles in the rotor, why not change the magnetic field in the stator? This would eliminate the need for the sparking commutator. Tesla saw that if the magnetic field in the stator rotated, it would induce an opposing electric field in the rotor, thus causing the rotor to turn.

Lesson One: Imagination and Reality Are Not the Same

In his vision in Budapest, Tesla had a hunch that the rotating magnetic field in his motor could somehow be produced using AC. However, at the time, he lacked the practical experience with AC equipment needed to know how to create a rotating field. Over the next five years, Tesla struggled to acquire the practical knowledge needed to realize his motor, and he obtained much of this knowledge while working for Edison companies in Europe and America.

Once the Budapest telephone exchange was up and running, Tesla and Szigeti moved to Paris to help the Edison organization install incandescent lighting systems. Shortly after joining the French Edison Company, Tesla was put to work designing dynamos for incandescent lighting installations.[6]

One of Tesla's major assignments was to install an Edison incandescent lighting system in the new railroad station in Strasbourg in Alsace. During the Franco-Prussian War of 1870-1, Strasbourg had changed from French to German hands. After the war, the German Empire established its presence in Strasbourg by erecting a series of substantial new public buildings, including a new central railroad station.[7] According to Tesla, the German authorities were quite upset with the Edison Company since the wiring in the plant had short-circuited and blown out a large part of a wall during a visit to the train station by Emperor William I.[8] To placate the Germans, the company needed to send a German-speaking engineer to finish wiring the new plant. Given his language skills, Tesla was sent to Strasbourg to reinstall the wiring and placate the German authorities.[9]

Although Tesla was soon working night and day on the Edison system, he found time to conduct experiments on his AC motor. Included in the railway station's electrical powerhouse was a Siemens AC generator which had probably been used to power an earlier arc-lighting system with Jablochkoff candles.[10] With Szigeti's help, Tesla constructed a small motor that could be powered by the Siemens AC generator. Anxious to keep the motor a secret, Tesla and Szigeti tested it in a closet where they could tap the AC circuit.[11]

For this motor, Tesla made the stator by winding insulated wire around the outside of an oblong brass ring.[12] The stator's windings were connected to the Siemens generator. For the armature, Szigeti made a five-inch iron disk which was mounted on a horizontal axle.[13] According to Tesla's mental engineering, the AC from the generator should produce a rotating magnetic field in the stator. In turn, the rotating field would induce currents in the disk; the induced currents would be repelled by the rotating field and thus the disk would rotate.[14] "It was," Tesla claimed, "the simplest motor I could conceive of. As you see it had only one circuit, and no windings on the armature or the fields. It was of marvelous simplicity."[15]

As simple as it was, this motor plainly did not work when Tesla first tried it.[16] When Tesla held the stator coil around the disk, the disk did not turn because he had wound the stator coil around a brass core which could not be magnetized.[17] To overcome this difficulty, Tesla jammed a steel file in the coil. Now the alternating current produced a magnetic field in the steel file which in turn induced currents in the iron disk. But still the disk didn't rotate and so Tesla tried the file in different positions relative to the disk. Eventually, he found a position where the magnetic field in the file and the induced currents in the disk were in the same direction, so that they repelled each other and caused the disk to slowly rotate. Tesla was thrilled to see the disk turn:

> I finally had the satisfaction of *seeing rotation effected by alternating currents of different phase, and without sliding contacts or commutator,* (Tesla's italics) as I had conceived a year before. It was an exquisite pleasure but not to compare with the delirium of joy following the first revelation.[18]

This experimental motor made Tesla aware of the phenomenon of magnetic lag, which would prove to be an important element in the design of his motors. Tesla realized that the magnetic field generated in the file did not reach its maximum strength when the current passing through the coil was at its maximum. Rather, because of Faraday's principles of induction, the magnetic field was created as the current was changing, and the field peaked when the current reached its minimum. This difference between the current and the induced magnetic field is known as magnetic lag, and Tesla subsequently used this phenomenon to design a number of practical AC motors.[19]

The Strasbourg motor was an important turning point for Tesla because this motor tempered his idealized thinking with a strong dose of practicality. Prior to this motor, Tesla had performed only mental engineering and he had taken for granted that what he could conjure in his mind's eye could be easily made to work in the real world. In Strasbourg, Tesla realized for the first time that materials count—the core of the stator needed to be made of iron or steel, not brass—and he came to appreciate how experiments could reveal new, useful phenomenon like magnetic lag. Even though he later insisted that he was able to design perfect machines in his head which would then run flawlessly when built, it is clear that, like all inventors and engineers, Tesla ran into problems when it came time to convert his ideals into working devices.

For our engineering students, then, Tesla's Strasbourg motor offers an important lesson: the real world does not always function as we would imagine it should. The nature of materials can often alter the ideal. In my view, this is a crucial lesson for engineering students to learn because so much of engineering is about moving ideas from the mind to the material world.

Lesson Two: Create an Effective Illusion

In 1884, thanks in part to the work he had done in Strasbourg, Tesla was transferred from Paris to the Edison Machine Works in New York. There, Tesla had little personal contact with Edison and was assigned the task of designing an arc lighting system. While the Edison Electric Light Company had pioneered incandescent lighting, the first Edison lamps were too dim for street lighting, which was the growth market for electric lighting in the mid-1880s. To capture a portion of the street lighting market from the rival Thomson-Houston and Brush Electric Companies, the Edison company needed an arc lighting system with lamps on the order of several thousand candlepower. Tesla threw himself into designing an arc lighting system, anticipating a handsome bonus. Unfortunately, just as Tesla completed his design, the Edison company shelved the project. With no bonus in sight, Tesla quit in disgust.[20]

Tesla was quickly hired by two business promoters from Rahway, N.J., Benjamin A. Vail and Robert Lane, who encouraged Tesla to patent his arc lighting system so they could commercialize it. Tesla unwisely assigned the patents to this shifty pair, trusting that they would manufacture equipment and compete with Edison. Vail and Lane, however, decided that the real financial opportunity lay in running a lighting company, not manufacturing equipment.[21] Once Tesla had his arc lighting system running in Rahway, his backers fired him and reorganized the firm. Abandoned by his patrons, Tesla fell on hard times and was forced to dig ditches.[22]

In the midst of hardship, Tesla mustered the energy to file in March 1886 a patent application for a thermo-magnetic motor--a novel device powered by heating and cooling magnets.[23] Discussions about his invention with the foreman at his ditch-digging job led to an introduction to Charles F. Peck. Intrigued by the thermo-magnetic motor concept, Peck offered to underwrite Tesla’s research. Because Peck was no technical expert, he invited Alfred S. Brown, a superintendent at Western Union, to join him in supporting Tesla. To permit Tesla to concentrate on inventing, Peck and Brown organized the Tesla Electric Company, rented a laboratory for him in Manhattan's financial district, and brought Szigeti from Europe to assist him. With support from Peck and Brown, the inventor devoted himself initially to developing the thermo-magnetic motor. When that concept proved unworkable, Peck encouraged Tesla to work on perfecting an electric motor.[24]

Taking Peck’s advice, Tesla now chose to work out the grand idea that had come to him in Budapest five years earlier: a motor with a rotating magnetic field. As a first step toward achieving this grand idea, Tesla had to test his hunch that several alternating currents could produce a rotating magnetic field. Up to now, he had thought a great deal about how several alternating currents might be combined, but he had never tried it in practice.

Tesla began by modifying the Weston DC dynamo in the lab so that it could produce two, three, or four separate alternating currents.[25] For his first experiments, he used a large laminated ring for the stator, similar to the one in his Strasbourg motor.[26] Rather than have a single winding around the ring as he did at Strasbourg, Tesla now divided the winding into four separate coils, one for each quadrant. Tesla had the AC generator deliver two separate currents to coils on opposite sides of the ring. For the motor's armature, Tesla balanced a shoe polish tin on a pin in the center of the ring. To Tesla's delight, the rotating magnetic field caused the tin can to spin, and he showed this model to Brown late in the summer of 1887.[27]

With this tin can armature, Tesla had finally figured out how to combine alternating currents to create a rotating magnetic field in the motor's stator. To do so, the currents delivered to each pair of coils had to be out of phase with one another. In the case of two currents, while one current was at its maximum positive value the other one had its maximum negative value. If one thinks of the alternating currents as sine waves, then one can say that these two currents are out of phase by 90°. Now understanding the importance of having the currents out of phase, Tesla was in a position where he could build a full-scale electric motor using the rotating magnetic field that he had envisioned in the park at Budapest.[28]

But now Tesla faced the challenge of convincing Peck and Brown that his AC motor was worth investing the time and money necessary to patent and promote it. Why should they put money into a spinning tin can? While it may seem obvious to us to develop an AC motor, it was not so to electrical experts in 1887. To understand why this was the case, we need to spend a few moments discussing the situation in the electrical industry in the mid-1880s.

On the one hand, Peck and Brown were probably comfortable with Tesla investigating motors because of the growing discussion in electrical circles about using motors in central stations. In the mid-1880s, as the number of central stations grew and the utility industry became more competitive, central station operators became quite interested in the possibility of expanding their customer base by adding motor service. While they would continue to provide electricity for lighting at night, central station operators saw motors as the means by which they could now provide electricity by day and sell power to factories and streetcar lines. In response, electrical manufacturing firms added motors to their product lines, and by 1887 there were fifteen firms in the field with a combined output to date of 10,000 motors.[29]

On the other hand, because most of these installed motors were powered by DC, Peck and Brown were highly suspicious of Tesla's ideas about developing an AC motor.[30] Nearly all of the central stations in the US in the mid-1880s were using DC, not AC. In Europe, though, inventors had been experimenting with AC. In particular, they investigated with what we now call a transformer; by winding two different coils on a single iron core, they found it was possible to alter the voltage of an alternating current.

By proportioning the coils in a transformer appropriately, one could raise or lower the voltage of alternating current, and inventors quickly realized that a transformer could be used in a variety of ways. For instance, in London in 1883, Lucien Gaulard and John Gibbs used one of the first transformers to connect both arc and different incandescent lights in series to a single large generator.[31] About the same time in Budapest, three engineers--Charles Zipernowski, Otto Titus Blathy, and Max Deri--saw AC as a way of developing an incandescent lighting system which could serve a wider area. By having their generator produce high-voltage AC, they found they could distribute power over longer distances using small copper wires. To protect customers from the high voltage, they used a transformer to step down the voltage before the current came into homes and shops. The ZBD system was manufactured by Ganz & Company, and within a few years, the system was being used successfully to light several European cities.[32] In both systems, the inventors chose to use single-phase AC since that was all that they needed in order to secure the desired voltage change.

The work in Europe on AC transformers was quickly appreciated by several astute American electrical entrepreneurs, including George Westinghouse. Having made a fortune by inventing the air brake and improved signaling systems for railroads, Westinghouse became interested in electric lighting in 1884. As a latecomer to the electrical industry, Westinghouse decided to bet on AC rather than DC, and he hired William Stanley, Jr. to develop an improved version of the Gaulard and Gibbs system. Building on Stanley's work, Westinghouse installed his first commercial AC system in Buffalo, New York in November 1886.

Peck and Brown were well aware of these trends in the electrical industry. They knew that, while there was growing interest in electric motors, no one was sure that the future belonged to AC. Hence, while Peck and Brown encouraged Tesla to investigate electric motors, they were not especially interested in having him work on an AC motor.

After several discouraging conferences with Peck and Brown to discuss his plans for an AC motor, Tesla realized that he needed a dramatic demonstration. It was not enough to show Brown a tin can spinning in a rotating magnetic field; he needed to do something that would capture the imagination of his backers.

Consequently, at their next meeting, Tesla asked Peck and Brown if they knew the story of the egg of Columbus. According to legend, Christopher Columbus overcame his critics in the Spanish court of Queen Isabella by challenging them to balance an egg on its end. After the scoffers were unable to get the egg to balance, Columbus made the egg stand upright by lightly cracking one end. Impressed that Columbus had outsmarted his critics, Isabella pawned her jewels to finance Columbus' ships.

When Peck and Brown acknowledged that they had heard the story, Tesla proposed that he could make an egg stand on end without breaking the shell. If he could go one better than Columbus, would Peck and Brown be willing to underwrite his AC experiments? "We have no crown jewels to pawn," replied Peck, "but there are a few ducats in our buckskins and we might help you to an extent."[33]

To gain those ducats, Tesla fastened his four-coil magnet to the bottom side of a wooden table and secured a copper-plated egg and several brass balls. When Peck and Brown next came to the laboratory, Tesla placed the copper egg on the tabletop and applied two out-of-phase currents to the magnet. To their astonishment, the egg stood on end, but Peck and Brown were stupefied when the egg and brass balls started spinning by themselves on the tabletop. While it looked like magic, Tesla quickly explained to Peck and Brown that the egg and balls were spinning because of the rotating magnetic field. Highly impressed by this demonstration, Peck and Brown became ardent supporters of Tesla's work on AC motors. They immediately hired a top patent attorney, Parker Page, to help Tesla file a series of patents for his motor.

This episode with the egg of Columbus taught Tesla that invention would require a degree of showmanship in order to create the right illusion about his creations. People don't invest in inventions built out of tin cans; they invest in projects that capture their imagination. To draw people in, one often has to draw on metaphors, stories, and themes that have power in a particular culture--that's what Tesla did by invoking the Columbus story. Once drawn in, Tesla could get Peck and Brown to think about the commercial potential of his motor.

Tesla and the egg of Columbus, then, illustrates for our students an important aspect of professional communications. It's not enough to convey the technical information to a non-technical audience--that is all the spinning tin can did. Effective communications often means putting the technical information in a context that captures the imagination and helps non-technical audiences envision the practical possibilities of a new technology. Finding the right illusion for different audiences--experts, investors, and users--should be regarded as an essential part of engineering.

Lesson Three: Follow Your Dream but Temper it with Practical Information

Once his egg of Columbus had convinced Peck and Brown, Tesla pushed ahead with building full-scale motors and filing patents. Guided by his patent attorney Parker Page, Tesla filed in the fall of 1887 a series of patents broadly covering AC motors using the principle of a rotating magnetic field. In these patents, Tesla introduced the idea that multi-phase (or as he said, polyphase) AC could be used to effectively transmit power over long distances.

For Tesla, the concept of using two separate alternating currents to produce a rotating magnetic field was a grand idea; it was simple, it was elegant, and it satisfied his aesthetic sensibility. Yet this grand idea bothered Tesla's backer Brown. In order to deliver two separate alternating currents to Tesla's motor, it was necessary to run four wires from the generator to the motor. Since the AC systems then being introduced by the Westinghouse and other companies employed only two wires, Brown recognized that Tesla's motor was not very practical.[34] Consequently, Brown challenged Tesla to design an AC motor which could run on two wires using single-phase AC. Within a few days, Tesla presented Brown with a variety of designs for what Tesla called split-phase motors. In these motors, Tesla split the single incoming current into two branches; by placing an induction coil in one branch and a resistor in the other, Tesla created two out-of-phase currents which could then run the motor. In addition, he also split the current using capacitors and transformers in novel circuits.[35]

Impressed with Tesla's split-phase motor ideas, Brown asked him to prepare patent applications for all his ideas. With his eye on developments in the electrical utility industry, Brown sensed that patents for AC motors which could be added to existing distribution networks would soon become valuable. Tesla, however, was worried that his attorney Page would file patent applications only for the practical split-phase motors and neglect the applications covering the grand principle of a rotating magnetic field. Consequently, Tesla did not tell Page about his split-phase designs for six months. It was only at the last minute that Page got Tesla to disclose the two-wire designs so that patents could be filed for both the broad principle and the specific applications.[36] This delay in filing weakened Tesla's long-term patent position and forced Tesla to engage in years of infringement litigation. Enthralled by the perfect idea of a rotating magnetic field, Tesla inadvertently compromised his legal and financial position.

Nonetheless, as it became clear that Tesla had come up with several promising AC motors (both polyphase and split-phase), his patrons began to think about how to promote them. Peck and Brown arranged for Tesla to lecture before the American Institute of Electrical Engineers in May 1888.[37] Timed to take place just a few weeks after Tesla's patents were issued, the lecture received extensive coverage in the electrical trade press and attracted Westinghouse. In July 1888, Westinghouse bought the rights to the Tesla patents for $25,000 in cash, $50,000 in notes and a royalty of $2.50 per horsepower for each motor.[38] Westinghouse offered such favorable terms because he was impressed that the patent portfolio contained both the broad polyphase patents as well as the practical split-phase designs. Westinghouse engineers subsequently modified Tesla's motors and developed a new AC system using three-phase, 60 cycle current. This new system was dramatically demonstrated at Niagara Falls in 1895, where power was transmitted 25 miles to factories in Buffalo. Tesla's invention of the AC motor and his idea of using multi-phase AC soon became the standard for transmitting electric power.

It would be easy to conclude from Tesla's reluctance to patent his split-phase motors that, like other inventors, Tesla had a blind spot about the commercial implications of his work. His contemporary, Elihu Thomson, for example, failed to appreciate fully the importance of developing a single-phase AC system using transformers, and Thomson only filed patents in 1885 when pushed by his patron, Charles A. Coffin.[39] However, this episode with the split-phase motors reveals an even stronger characteristic of Tesla's style as an inventor. Tesla was anxious to develop his polyphase system because it perfectly embodied an ideal principle. Throughout his AC motor work, he was enthralled by the idea of capitalizing on the symmetry of an AC system: just as several alternating currents were produced as an armature rotated through the magnetic field of a generator, so several alternating currents could produce motion in the motor by means of a rotating magnetic field. While Tesla could utilize this ideal symmetry in his polyphase system, he could not do the same with split-phase motors. Yes, he could split the current using a variety of ingenious tricks, but these tricks were not the same as employing a beautiful principle.

Over the course of his career, Tesla's strength was to identify a grand idea and to develop a system around it. The difficulty with this approach was that it meant that Tesla expected businessmen and consumers to adjust to his systems--based on an ideal--rather than Tesla adjusting his systems to the needs and wishes of society. In the case of his polyphase versus split-phase motors, it meant that Tesla thought that society ought to adopt his beautiful polyphase system even if it meant replacing the existing two-wire, single-phase systems with the more expensive four-wire networks needed for polyphase. Practical considerations and cost meant little to Tesla in comparison to an ideal principle.

The morale to the story of Tesla's split-phase patents is to follow your dream but temper it with practical information. Listen to your business advisors because they might know something that could make the difference between success and failure. It is all too easy to follow the classic dichotomy of the brilliant engineer and the dumb businessman, as exemplified in both the cartoon strip "Dilbert" and the sociology of Max Weber. Every time Dilbert the engineer has a great idea, he is opposed by his dumb manager who only considers marketing issues. Weber argued that charisma, the creative spirit, is always in opposition to the bureaucratic urge, that business always dilutes the spirit. Yet, I would argue that successful innovation involves both charisma and bureaucracy. Brilliant inventions only come to be part of everyday life when business organizations tackle the formidable problems of manufacturing and marketing a new product. And rather than diluting a great idea, marketing considerations can sometimes refine and improve the idea. This is what happened when Brown asked his question about making a motor that could run on two wires--it set the stage for Tesla to receive patents for a wider range of inventions and hastened the introduction of his motor. Perhaps we need to invite our engineering students to be a bit like both Tesla and Brown--to be enthralled by beautiful ideals but also be able to relate them to the practical business world.

Footnotes

Acknowledgments: This research on Tesla has been supported by a grant from the Alfred P. Sloan Foundation. I am grateful to the staff of the Nikola Tesla Museum in Belgrade, Yugoslavia for sharing with me the published testimony that I cite below.

[1]Previous biographies of Tesla include Thomas Commerford Martin, *The Inventions, Researches, and Writings of Nikola Tesla* (New York: The Electrical Engineer, 1894; reprinted Barnes & Noble, 1995); John J. O'Neill, *Prodigal Genius: The Life of Nikola Tesla* (New York: Ives Washburn, 1944; reprinted Albuquerque, New Mexico: Brotherhood of Life, 1994); Inez Hunt and Wanetta Draper, *Lightning in His Hand; The Life Story of Nikola Tesla* (Hawthorne, California: Omni Publications, 1964); Margaret Cheney, *Tesla: Man Out of Time* (New York: Prentice-Hall, 1981); Mark J. Seifer, *Wizard: The Life and Times of Nikola Tesla:* (New York: Birch Lane Press, 1996); and Margaret Cheney and Robert Uth, *Tesla: Master of Lightning* (New York: Barnes & Noble, 1999).

[2]For the Tesla Memorial Society of New York, see www.teslasociety.com. From 1984 to 1999 the International Tesla Society held annual conferences and published proceedings. There are dozens sites on the World Wide Web devoted to his life and inventions as well as two hobbyist groups dedicated to experimenting with his inventions, the Tesla Coil Builders Association and the Tesla Engine Builders Association. For more information on the restoration efforts at Wardenclyffe, see www.teslascience.org.

[3]Tesla (hereafter cited as NT) attended this school from 1875 to 1878; see a copy of his course transcript in Kenneth Swezey Papers, Archives Center, National Museum of American History, Washington, DC, Box 7, Fol. 13. According to Austrian historian Klaus Plitzner, the Joanneum was founded in 1811 as a result of a gift from Archduke John (Joanneum) to the counts of Styria (an Austrian province). In 1864, it became a *Technische Hochschule,* and in the twentieth century, it trained the engineers who founded Porsche and Volkswagen.

[4]NT, "My Inventions," *Electrical Experimenter,* May-October 1919; reprinted as *My Inventions: The Autobiography of Nikola Tesla,* ed. B. Johnston (Williston, Vt.: Hart Brothers, 1994), 57.

[5]NT, *My Inventions,* 61.

[6]NT testimony in *Complaint's Record on Final Hearing, Volume 1-Testimony, Westinghouse vs. Mutual Life Insurance Co. and H. C. Mandeville* [1903], Item NT 77, Nikola Tesla Museum, Belgrade, Yugoslavia, 187-8, 195, 306.. Hereafter cited as NT *Testimony*.

[7] The station was completed in 1883 and at some point in the nineteenth century, the station was lit by 2000 electric lamps. See Julius Euting, *A Descriptive Guide to the City of Strassburg and its Cathedral,* 7 ed. (Strassburg: Karl J. Trübner, n.d.), pp. 84-5.

[8] In reviewing biographies of Emperor William I, I found mention of only one visit by the Emperor to Strasburg between 1878 and 1884, a visit which took place in September 1879. Given that there had been two assassination attempts against the Emperor in 1878 and that the Alsatians were not happy being under German rule, it is surprising that no reference is made in his biographies to an event like a wall exploding near the emperor in a politically sensitive place such as Strasburg. See Paul Wiegler, *William the First: His Life and Times,* trans. C. Vesey (Boston: Houghton-Mifflin, 1929), 377 and Edouard Simon, *The Emperor William and His Reign,* 2 vols. (London: Remington, 1888), 2:189.

[9] NT *Testimony*, 185-6 and NT, *My Inventions*, 67.

[10] NT *Testimony*, 188. For an illustration and description of this generator, see von Urbanitzky, *Electricity in the Service of Man,* 296-99. See also Silvanus P. Thompson, *Dynamo-Electric Machinery,* 3rd ed. (London, 1888), 267-8. The armature of this generator was equipped with twelve individual bobbin windings and so it is likely that this generator produced six-phase AC.

[11]A. Szigeti, deposition, 7 Feb. 1889 in *Tribute to Nikola Tesla: Presented in Articles, Letters, and Documents* (Beograd: Nikola Tesla Museum, 1961), A-400. Hereafter cited as Szigeti, 1889 deposition.

[12] Tesla recalled that the ring was approximately 7 inches on the long sides and between 1 and 1.5 inches on the narrow sides. To prevent eddy currents from being generated in the brass ring, he fashioned it from a series of thin metal sheets and he cut a slot through the ring. Tesla did not mount the stator ring but rather held it in his hand; he recalled that it grew quite hot when the current was passing through it. NT *Testimony*, 181 and 192.

[13]Szigeti, 1889 deposition, A-400.

[14] Tesla steadfastly maintained that he was not influenced by any antecedent devices in developing his designs. However, his Strasburg motor bears a striking resemblance to an electromagnetic gyroscope introduced by De Fonvielle and Lontin in 1880. According to Thompson, these two electricians found "that a lightly pivoted copper disk could be maintained in continuous rotation--if once started—by being placed, in the presence of a magnet, within a coil of copper wire wound on a rectangular frame (like the coil of an old galvanometer), and supplied with alternate currents from an ordinary Ruhmkorff induction coil." See Silvanus P. Thompson*, Polyphase Electric Currents and Alternate-Current Motors*, 2 ed., (London: E&FN Spon, 1900), 428. When presented during cross-examination with a paper describing the De Fonvielle and Lontin device, Tesla claimed there was no resemblance between his motor and their device since the armature in his motor started to turn on its own. See NT *Testimony*.

[15] Quote is from NT *Testimony*, 220. In his patent testimony, Tesla reported that this motor was subsequently included in one of his patents; see NT *Testimony*, 184. See "Electric Magnetic Motor," U.S. Patent 424,036 (filed 20 May 1889, granted 25 March 1890), especially figure 3. It is also mentioned in Thomas Commerford Martin, *The Inventions, Researches, and Writings of Nikola Tesla,* 2 ed., (1893; rep. New York: Barnes & Noble, 1995), 69.

[16]NT *Testimony,* 182.

[17] In discussing in his basic textbook about how a helix or coil of wire can be used to create an electromagnet, Silliman explained "If the helix is wound on a tube of glass, paper, or wood, these substances offer no resistance to the passage of the [magnetic] power; but if a tube of copper or other metal were employed, the magnetizing power of the current on the enclosed bar would be destroyed." See Benjamin Silliman, *Principles of Physics, or Natural Philosophy,* 2 ed. (Philadelphia, Theodore Bliss, 1863), p. 608.

[18] Quote is from NT, *My Inventions,* 67. Tesla explained how this motor worked in NT *Testimony*, 177-82 and 284. For the problem of getting the file in the right position, see Szigeti, 1889 deposition, A-400.

[19] NT *Testimony*, 257.

[20]NT *Testimony*, 193.

[21]Entry for Tesla Electric Light and Mfg. Co., New Jersey, Vol. 53, p. 159, R. G. Dun & Co. Collection, Baker Business Library, Harvard University.

[22]O'Neill, *Prodigal Genius,* 65.

[23]NT, "Thermo-Magnetic Motor," US Patent 396,121 (filed 30 Mar. 1886; granted 15 Jan. 1889). See also Martin, *Inventions, Researches, and Writings,* 424-8.

[24]NT *Testimony*, 213.

[25] I suspect that he used a DC dynamo which Weston had developed for electroplating which had an armature with 6 projecting poles. By replacing the DC commutator with AC slip rings, Tesla could have drawn 2 or 3 separate currents off of this dynamo. See NT *Testimony*, 200-1 and 210 as well as Thompson, *Dynamo-Electric Machinery,* 280. Tesla's patents for the fall of 1887 suggest that he also tried using several both ring-wound and drum-wound armatures in this generator.

[26] Sometime in the Fall of 1887, Tesla did build a motor just like the one he had in Strasburg and he operated it on single-phase AC. See NT *Testimony*, 183-4 and 210-1. This motor was later included in NT, "Electro Magnetic Motor," U.S. Patent 424,036 (filed 20 May 1889, granted 25 March 1890), figure 3.

[27] NT *Testimony*, 21.

[28] The discerning technical reader and Tesla admirer may be quite rightly wondering why I attribute the discovery of having the currents out of phase to 1887, not 1882. Previous biographers have assumed that if Tesla said in his autobiography that he understood everything about his AC motor in the Eureka moment in the park, then he must have known everything, including the importance of using several currents out of phase. After carefully studying Tesla's statements in his autobiography and in patent testimony and investigating what was known about AC in the early 1880s, I have come to the conclusion that it would have been exceptional for him to be thinking about AC in terms of phase in 1882. The topic was simply not widely discussed in textbooks available circa 1882. Moreover, if he had known about the importance of using two alternating currents out of phase, why did he not experiment with such currents with his motor in Strasburg in 1883? Instead, I think the most sensible way to establish when Tesla had this insight is to pay attention to when he first started using out of phase currents in his experiments and that was in the summer and early fall of 1887.

[29] Louis C. Hunter and Lynwood Bryant**,** *A History of Industrial Power in the United States* (Cambridge: MIT Press, 1991), Vol. 3, 210.

[30] "Tesla's Egg of Columbus," *Electrical Experimenter* 6:774-5ff. (March 1919) on 775.

[31] Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore: Johns Hopkins University Press, 1983), 87-91.

[32] Hughes, *Networks of Power,* 95-7.

[33] "Tesla's Egg of Columbus," 775.

[34]NT *Testimony,* 160, 173-4, and 210.

[35]NT *Testimony,* 159, 174-5, 230, 289, and 369-72. Patent 511,560 summarizes many of these techniques.

[36]NT *Testimony,* 316-8, 329, 416, 418, and 426.

[37] NT, "A New System of Alternating current Motors and Transformers," in Martin, *The Inventions, Researches, and Writings of Nikola Tesla,* 10-44.

[38]"Agreement of July 7, 1888," in *Complaint's Record on Final Hearing, Volume 2-Exhibits, Westinghouse vs. Mutual Life Insurance Co. and H. C. Mandeville* [1903], Item NT 74, Nikola Tesla Museum, Belgrade, Yugoslavia, 584-7. See also NT *Testimony,* 327

[39]W. Bernard Carlson, *Innovation as a Social Process: Elihu Thomson and the Rise of General Electric, 1870-1900* (New York: Cambridge University Press, 1991), 251-2. Alexander Graham Bell was also slow to appreciate the commercial implications of the telephone, and was guided by his patron and future father-in-law, Gardiner G. Hubbard; see W. Bernard Carlson, "Entrepreneurship in the Early Development of the Telephone: How did William Orton and Gardiner Hubbard Conceptualize this New Technology?" *Business and Economic History* 23:161-92 (Winter 1994).

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